# Status of Eutrophication in San Elijo Lagoon and its Relevance for Restoration

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## Executive Summary

San Elijo Lagoon (the Lagoon) in San Diego County, California, is undergoing restoration planning to ameliorate problems associated with human impacts on hydrology, habitat and water quality. Increased watershed and nutrient runoff, legacy sewage disposal, and restricted tidal exchange have caused a buildup of organic matter in Lagoon sediments. This accumulated organic matter, otherwise known as eutrophication, causes nuisance algal blooms, consumes dissolved oxygen (DO), causing hypoxia and related fish kills, and degradation of benthic habitat that provides important forage for estuarine fish, resident and migratory birds. Collectively, these symptoms of eutrophication have caused the Lagoon to be placed on the 303(d) list of impaired waterbodies.

The San Elijo Lagoon Restoration Project (SELRP) was proposed to improve ecological function and services of the Lagoon by two primary means: 1) reconfiguring lagoon elevations via grading/dredging to support specific habitat types and to remove legacy sediment organic matter from sewage disposal sites and 2) modifying water flow in the Lagoon via changes to the ocean inlet and lagoon channels. As the SELRP nears completion of the restoration permitting process, additional documentation of the status of eutrophication symptoms in the Lagoon is desired by SELC in order to support decision-making on the restoration by SELRP lead agencies.

The goal of this report is to summarize the status of eutrophication symptoms in the Lagoon, utilizing existing data collected through SELC, Bight Regional, and County monitoring programs and other available special studies (2003 – 2016). The report in particular attempts to answer the question: What is the magnitude, frequency, extent and duration of eutrophication symptoms relative to existing guidance or benchmarks of adverse effects? Ultimately, the intent is to use this information to increase understanding of how severe eutrophication symptoms are, to support discussions on the importance of water and sediment quality in determining the preferred restoration option, considering whether such actions are likely to ameliorate such conditions.

Three lines of evidence were used to assess eutrophication status of the Lagoon: 1) macroalgal biomass and percent cover, 2) DO and 3) benthic macroinvertebrate (BMI) taxonomic composition, the latter of which is a line of evidence in the State Water Board's sediment quality objective triad. Existing data from the period to 2003-2016 were interpreted through existing policy or draft scientific guidance in order to make an assessment of eutrophication.

We found that the Lagoon is failing to meet water and sediment quality objectives for two of the three lines of evidence (DO and BMI) and is meeting, but only nearly so, a proposed numeric target for macroalgae.

The DO dataset was the most extensive, monitored continuously at five sites and spanning from 2003-2016. These data indicate that during the spring-fall, DO in the Lagoon was in suboptimal DO conditions typically at least half the time (DO conditions that can affect fish reproduction, larval recruitment, and juvenile survival). Hypoxia, conditions that can cause acute mortality of fish and some invertebrate species, occurred at all sites from 15-76% of the time across all sites.

The duration of these hypoxic events were at a frequency to be of significant concern for the potential impact on biological resources. Low DO was significantly correlated to temperature, a driver that is likely to increase with climate change. The BMI data spanning the same time period are consistent with this suggested potential for biological impact, as nearly all of the sites are in a highly disturbed condition throughout the period 2003-2013. On the whole, the BMI community data suggest that excess organic matter accumulation, salinity, and DO were the primary structuring factors of community composition, with salinity fluctuation (and possibly low DO) likely being more important in the upper portions of the estuary, while sediment organic matter was an important influence throughout.

Lagoon restoration is an appropriate management action to consider improving the documented sediment and water quality problems, as these conditions appear to be impacting the basis for estuarine fish and bird food webs. McLaughlin et al. (2010) noted that the efflux of nutrients associated with Lagoon sediment organic matter represents > 70% of total dry weather nutrient inputs to the Lagoon. This mechanism assures that eutrophication symptoms will continue, even if watershed nutrient loads are drastically reduced. Three types of actions could improve eutrophication symptoms: 1) improved tidal exchange, reducing hydraulic retention times, 2) improving Lagoon circulation to flush out fine grained sediments and opportunities to allow water to stagnate, and 3) removal of sediments high in organic matter and nutrient content, particularly those associated with legacy sewage disposal. A combination of these actions are anticipated to be the most effective approach to address eutrophication in the system, as it would reduce *in situ* accumulated sediment organic matter within the Lagoon and minimize the accumulation of new sources of organic matter, thereby reducing eutrophication symptoms. These three actions are consistent with the preferred restoration alternative.

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## ACKNOWLEDGEMENTS

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# I. INTRODUCTION

## 1.1 Background and Context

San Elijo Lagoon (the Lagoon) is a bar-built estuary located within the southern portion of the city of Encinitas in San Diego County, California. The Lagoon is part of a 960-acre reserve of estuarine, freshwater, riparian and upland open space habitat that supports a large number of functional habitats and wildlife, including populations of federally- or state-listed endangered species such as the light footed Ridgway's rail, willow flycatcher, California gnatcatcher, western snowy plover, and Belding's savannah sparrow. The Lagoon drains the Escondido Creek watershed, which encompassed 200 $km^2$ and drains through two main tributaries: Escondido Creek and Orilla Creek. Urban and agricultural land uses in the watershed resulted in hydrological modifications to the Lagoon and have led to increased nutrient loading to the estuary. Between 1940 and 1973, municipal wastewater was discharged into Escondido Creek and the Lagoon itself (Coastal Conservancy 1996). The ecological effects of increased runoff and legacy sewage disposal have been compounded by water obstructions to and from the Pacific Ocean by roads and railroad infrastructure. These constraints on the hydraulic connection between the ocean and lagoon affect tidal exchange and drainage of freshwater flows. Together, these actions have resulted in an alteration in the balance of habitats within the lagoon (e.g., between unvegetated and vegetated intertidal habitats). The increased watershed nutrient loads and legacy sewage deposits have also caused eutrophication[1] of Lagoon subtidal and intertidal habitats, as evidenced by macroalgal blooms, poor benthic habitat quality, low dissolved oxygen (DO) in surface waters, resulting in occasional fish kills (Figure 1; McLaughlin et al. 2010). Because of issues, the Lagoon was placed on the State Water Resources Control Board's (SWRCB) 303(d) list of impaired waterbodies (Figure 1).

The San Elijo Lagoon Restoration Project (SELRP) was proposed to improve ecological function of the Lagoon by two primary means: 1) reconfiguring lagoon elevations via grading/dredging to support specific habitat types and to remove legacy sediment organic matter from sewage disposal sites and 2) modifying water flow into the lagoon via changes to the ocean inlet and lagoon channels. Reconfiguring the lagoon would be accomplished by grading and dredging in some areas, which would remove organic rich sediments that support eutrophication in the lagoon. The need for such removal was informed in part by previous studies, which found that organic rich sediments in the Lagoon were responsible for strong sediment oxygen demand and for high efflux of sediment nutrients (a.k.a. benthic flux) that is largely responsible for supporting an overabundance of macroalgal blooms. McLaughlin et al. (2010) concluded specifically,

> "Sediment data indicate that the Lagoon has accumulated a large amount of organic matter. Because benthic flux is the major source of N to the Lagoon, recycling of this

[1] Eutrophication is defined as the increase in the rate of supply (from watershed transport or direct disposal) and/or *in situ* production of organic matter from algae and aquatic plants in a water body (Nixon 1995).

organic matter to biologically available forms of nutrients will likely continue to cause problems with algal blooms and hypoxia, even with nutrient reductions [from the watershed], unless restoration is undertaken to flush [or remove] the Lagoon of the fine-grained sediments and improve circulation."

As the SELRP nears completion of the restoration permitting and final design, additional documentation of the status and trends of eutrophication symptoms in the Lagoon is desired by SELC in order to support decision-making on the restoration by SELRP lead agencies. In the fall 2015, SCCWRP provide a brief presentation to SELRP lead agencies of a series of special studies conducted in 2008-2010 intended to establish the baseline condition of SELC with respect to eutrophication (McLaughlin et al. 2010, McLaughlin et al. 2013). Following this presentation, it has become apparent from stakeholder feedback that additional clarity is needed, in the form of a written summary and presentation which incorporates any new data and clarifies the pathways of potential impact to ecosystem services and beneficial uses.

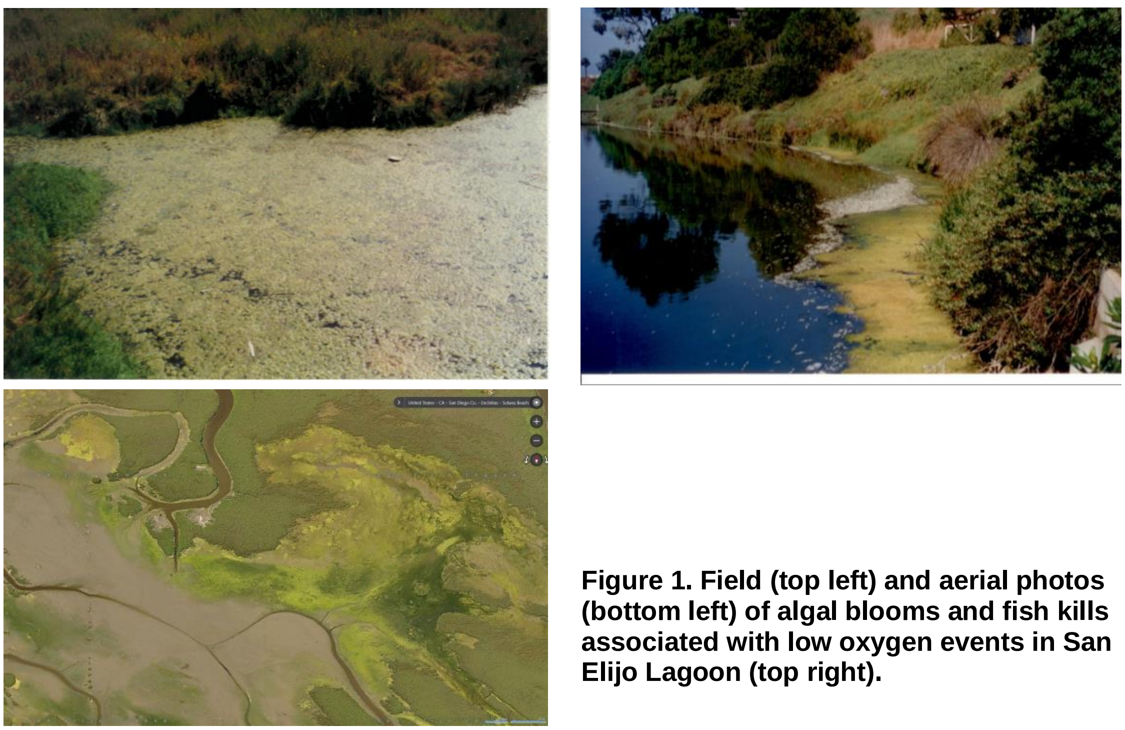


**Figure 1. Field (top left) and aerial photos (bottom left) of algal blooms and fish kills associated with low oxygen events in San Elijo Lagoon (top right).**

## 1.2 Goal and Key Questions

The goal of this report is to summarize the status of eutrophication symptoms in the Lagoon by utilizing existing data collected through SELC, Bight Regional, and County monitoring programs (2003 – 2016) and other available special studies. The report in particular attempts to answer the question: What is the magnitude, frequency, extent and duration of eutrophication symptoms relative to existing guidance or benchmarks of adverse effects? Ultimately, the intent is to use this information to increase understanding of how severe eutrophication symptoms are, to support discussions on the importance of water and sediment quality in determining the preferred restoration option, considering whether such actions are likely to ameliorate such conditions.

## II. METHODS

A simple conceptual model of estuarine ecological response to eutrophication is helpful to understand why the eutrophication symptoms of interest can have an adverse effect on ecosystem services and beneficial uses (Figure 2). The increased nutrient loads, alterations in hydrology, sedimentation, and temperature can result in three types of ecological response: 1) Changes to aquatic primary producers – in this case, an overabundance of macroalgae and a propensity towards harmful algal blooms and associated toxins, 2) altered water and sediment biogeochemistry, including hypoxia or suboptimal concentrations of DO in surface waters and sediment, and 3) altered community structure of benthic and water column invertebrates and tertiary consumers (fish, birds, mammals). These ecological responses include adverse effects on both ecological and human endpoints of concern. This cascade of effects has a direct effect on the ecosystem services and beneficial uses an estuary provides, including reduced: 1) habitat for aquatic life (including EST, MAR, WILD beneficial uses), 2) protection of biodiversity including rare, threatened and endangered species and migratory and spawning habitat (RARE, SPWN, MIGR beneficial uses), 3) productivity of commercial and recreational fisheries (SHELL, COMM, AQUA beneficial uses), 4) good aesthetics and lack of odors (REC2 beneficial uses), and 5) maintenance of good water quality and taste (REC1, COMM, AQUA, SHELL beneficial uses) as well as aesthetics (REC2).

An analysis of existing data was conducted to assess the status of eutrophication symptoms in the Lagoon, linking to three primary symptoms illustrative of pathways of eutrophication impairment shown this simple conceptual model (Figure 2):

1) Water column DO (Diaz 2001);
2) Macroalgal biomass and percent cover (Valiela et al. 1997); and
3) Benthic macroinvertebrate (BMI) community composition, where available (Diaz and Rosenberg 1995).

Lagoon hydrology, nutrient loading and legacy organic wastes deposited within the Lagoon form a suite of stressors that work in concert to degrade biological condition. However, here we focus on the symptoms of eutrophication that are the results of this combined set of stressors, rather on the stressors themselves. The suite of indicators listed above provide direct evidence of ecosystem health and beneficial use support, rather than that which can be inferred from analyses of hydrology or nutrient loading (Sutula 2011).

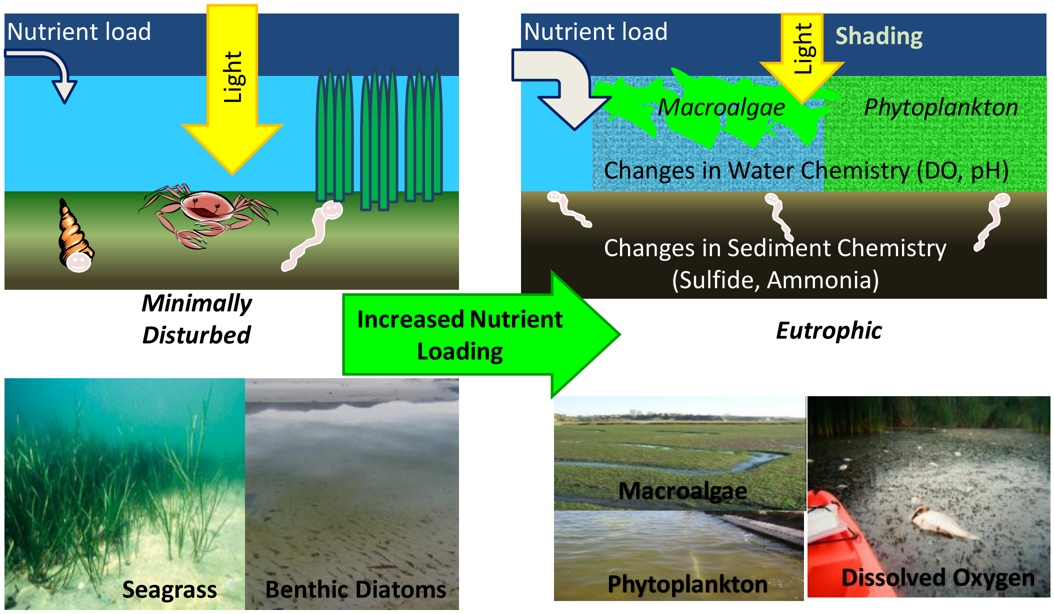



**Figure 2. Conceptual model of pathways of adverse impacts to ecosystem services from eutrophication in bar-built estuaries, including: 1) shifts in dominant primary producers, 2) changes in sediment chemistry from high organic matter accumulation, including increased (toxic) porewater sulfide and ammonia and reduction in denitrification, 3) changes in the structure and function of benthic invertebrate community, including loss of key taxa supporting the estuarine food web, and 4) increased water column hypoxia and anoxia.**

Table 1 summarizes the assessment frameworks that were used to assess eutrophication symptoms in the Lagoon, while subsequent sections provides detailed methods for each line of evidence. Macroalgal biomass and cover were assessed using the proposed framework of Sutula et al. (2016), which assesses an estuarine segment based on the peak of monthly biomass and cover during the growing season (April- November). Continuous DO data from the Lagoon was used to assess the frequency and duration of excursions of existing water quality objectives and from benchmarks that represent acute and chronic endpoints of physiological effects on fish and invertebrates. Available BMI data were assessed using the Bay et al. (2012) sediment quality objectives framework, with causal assessment of potential stressors where available data permitted such analysis. Figure 3 shows the locations of these stations in the Lagoon.

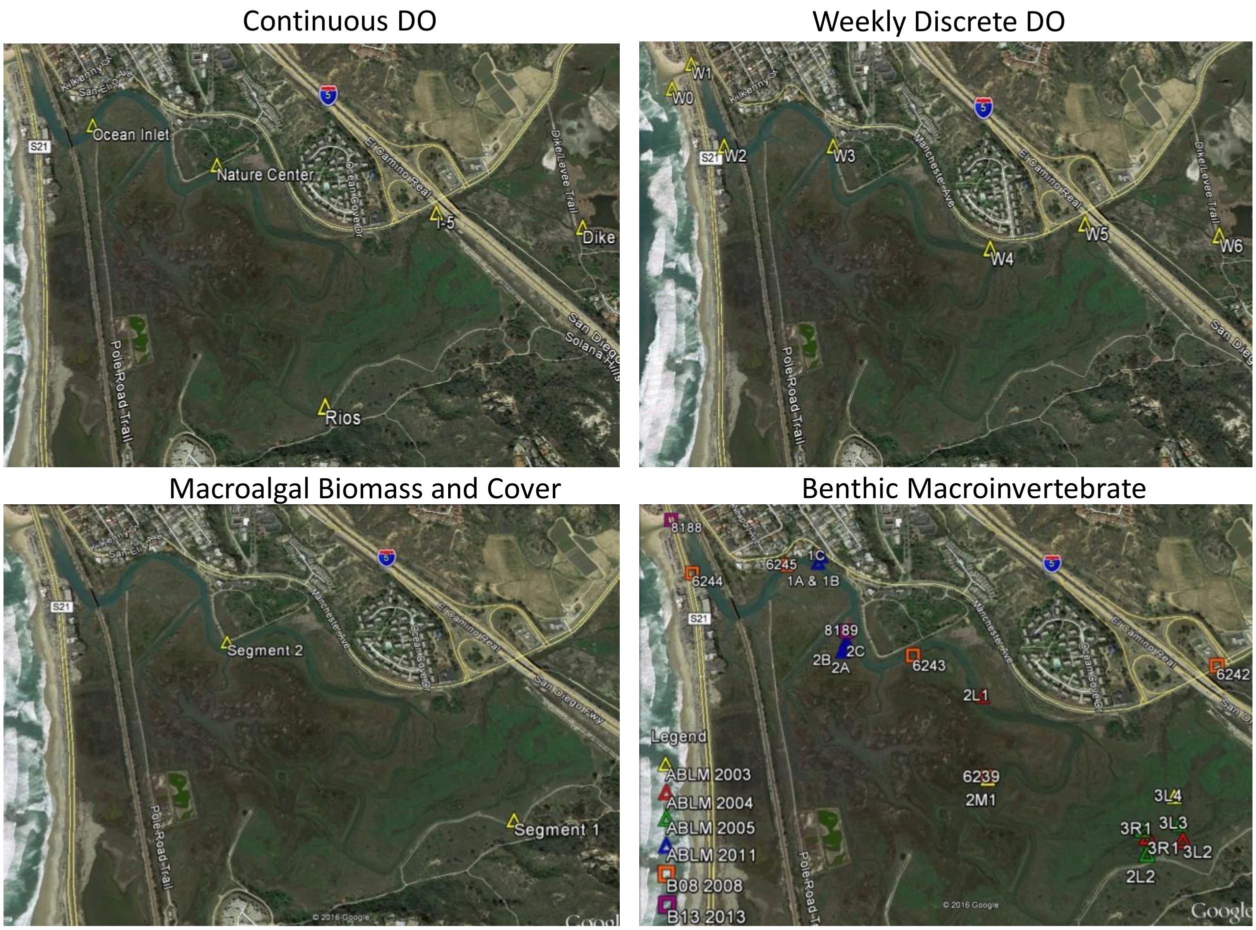



**Figure 3. Locations of various water quality, continuous data sonde and biological assessment monitoring in San Elijo Lagoon, by program type. Macroalgal biomass and percent cover was measured in three transects at each sites (Table 2). Continuous DO was measured via data sonde (Table 3). Discrete DO et al. water quality parameters was measured early morning (Table 4). Benthic macroinvertebrates are measured via discrete grabs (Table 2).**

**Table 1. Existing water quality objectives and interpretation frameworks that will be used to support this assessment.**

| Indicator | Reference |
|---|---|
| DO | San Diego Regional Water Quality Control Board Basin Plan, State Water Resources Control Board Listing Policy www.waterboards.ca.gov/water_issues/programs/tmdl/docs/ffed_303d_listingpolicy093004.pdf |
| | Sutula et al. (2013). Use of the benchmarks cited in this report helps to provide additional interpretation with respect to potential impact of frequency and duration of periods in which DO drops below established chronic and acute benchmarks. |
| Macroalgal Biomass and Cover | Sutula et al. (2016). Synthesis of Science and Proposed Frameworks for Assessment of Eutrophication in California Estuaries: Macroalgae. Document is in review, pending feedback from Water Board staff. |
| BMI Community Composition | Sediment Quality Objectives (SQO) Benthic Line of Evidence (BLOE) assessment framework (Bay et al. 2012), with analyses of benthic community composition data for information on possible stressors, such as eutrophication (low DO, organic matter accumulation) versus other stressors that might depress benthic habitat quality scores but are unrelated to eutrophication-related stress. |

## 2.1 Assessment of Macroalgal Biomass and Percent Cover

Excessive macroalgal blooms have a variety of negative effects on estuaries including: 1) increasing frequency of water column and sediment hypoxia and heightening heterotrophic bacterial activity, resulting in poor water quality and increased frequency of diseases, 2) alteration of biogeochemical cycling, more rapid nutrient regeneration (Tubbs and Tubbs 1980; Raffaelli et al. 1991; Wennhage and Pihl 1994; Bolam et al. 2000), 3) shading or smothering of seagrass, shellfish beds and other important habitats (Nelson 2009, Young 2009), 4) decreased recruitment and survival of benthic invertebrates and reduced carrying capacities for fishes and shorebirds (e.g., Raffaelli 1999; Thomsen and McGlathery 2006; Nezlin et al. 2009), 5) poor aesthetics and an increase in odors relating to the decomposition of organic matter and increased sulfide production, and 6) subsequent changes in both trophic and community structure of invertebrates, birds and fishes (Raffaelli et al. 1989, 1991; Bolam et al. 2000). Cumulatively, these adverse effects result in a reduction in recreational use of estuarine waters (REC1 and REC2), poor water column and benthic habitat quality for estuarine (EST) and marine (MAR) aquatic species, direct impacts to populations of threatened and endangered (RARE), migratory (MIGR) and spawning (SPAWN) birds, fish and mammals, and reduction in the economic value of commercial and sports fisheries, aquaculture, and shellfish harvesting (COMM, AQUA).

In San Elijo Lagoon, as in most other Southern California bar-built estuaries, macroalgae is the dominant primary producer in eutrophic conditions, with biomass several orders of magnitude higher than phytoplankton (McLaughlin et al. 2013a, McLaughlin et al. 2013b). Macroalgal biomass and percent cover data collected over a 2-year period were used as a line of evidence to assess eutrophication in the Lagoon (Table 2).

**Table 2. List of macroalgal and BMI datasets available for San Elijo Lagoon**

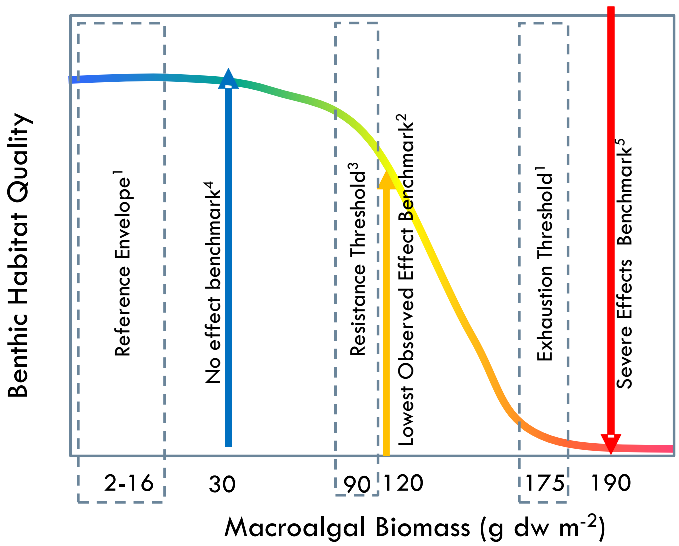
| Indicator | Program | Dates and Frequency |
|---|---|---|
| Macroalgal biomass and percent cover | Prop 13 Special Studies in Support of Monitoring Order | Quarterly, January-October 2008 |
| | Bight 08 Eutrophication Assessment | Bimonthly, November 2008-October 2009 |
| BMI community composition | Bight 08 Contaminant Impact Analysis | 1 site-2003, 5 sites-2008, 2 sites-2013 |
| | MS4 Lagoon Monitoring Program | Various dates from 2003-2013 |

Scientific synthesis and studies supported by the State Water Board for their nutrients policy are relevant as benchmarks to assess the effect of macroalgal biomass and cover on the Lagoon ecosystem services and beneficial uses (Figure 4; Sutula et al. 2016, Sutula et al. 2014, Green et al. 2013). These studies have been synthesized into a single "assessment framework" which utilizes a combination of percent cover and biomass to categorize an estuarine segment into ecological condition categories from "very high" to "very low" (Table 3, Sutula et al. 2016), an approach originally adopted by the European Union to implement their Water Framework Directive (Scanlan et al. 2007). In the EU, a "moderate" rating represents a tier in which management action is warranted. In the case of the Sutula et al. (2016) framework, the Water Board has not yet established a nutrient policy for estuaries. However, the San Diego Regional Board has utilized Sutula et al. (2016) and associated studies to establish numeric targets for several estuary TMDLs. Most recently the numeric target proposed for the Santa Margarita River Estuary TMDL is the growing season maximum monthly biomass < 57 g dw $m^{-2}$; no percent cover target is currently proposed (C. Gorham, SD Water Board, personal communication).

**Table 3. Proposed classification of macroalgal abundance as a function of dry weight biomass and percent cover. Combination of biomass are cover are ranked from low macroalgal abundance = very high ecological condition (blue) to high macroalgal abundance = very low ecological condition (red). From Sutula et al. (2016).**

| | (g dw $m^{-2}$) | %Percent Cover | | | | |
|---|---|---|---|---|---|---|
| | | < 10 % | 10-25 % | 25-40 % | 40-70 % | > 70 % |
| Biomass | >175 | Moderate | Low | Low | Very Low | Very Low |
| | 100-175 | Moderate | Moderate | Low | Very low | Very Low |
| | 70-100 | Moderate | Moderate | Low | Low | Low |
| | 50-70 | High | High | Moderate** | Moderate** | Low |
| | 15-50 | Very High | High | High | Moderate | Moderate |
| | < 15 | Very High | Very High | High | High | Moderate |

** downgrade if moderate for 2 consecutive sampling periods




Literature Cited

1. California Field Study, Sutula et al. 2014
2. California Experiments, Green et al. 2013
3. Venice Lagoon Field Study, Bona 2006
4. European Mediterranean Experiment, Cardoso et al. 2004
5. California Experiment, Green (2011)

**Figure 4. Synthesis of literature informing range of macroalgal biomass that represents "reference," benchmarks of no observed effects and lowest observed effects established by controlled experiments. Thresholds are established by statistical analyses of field studies demarking intial points of decline of benthic habitat quality ("resistence") and points at which sediments were azoic (without any benthic invertebrates, "exhaustion").**

## 2.2 Assessment of DO

DO is necessary to sustain the life of all aquatic organisms that depend on aerobic respiration. Eutrophication produces excess organic matter that fuels the development of surface water hypoxia (i.e. surface water DO concentration < 2.8 mg DO L-1) and, in some cases, anoxia (<0.5 mg DO L-1) as that organic matter is respired (Diaz 2001). The response of aquatic organisms to low DO will depend on the intensity of hypoxia, duration of exposure, and the periodicity and frequency of exposure (Breitburg et al. 1997, 2009, Zaldivar et al. 2008). Organisms have developed several physiological and behavioral adaptations to deal with temporary periods of low oxygen availability. Organisms can: 1) temporarily utilize anaerobic pathways to produce energy (ATP); 2) scavenge oxygen from hypoxic waters and increase the efficiency of oxygen transport to cells; 3) emigrate from hypoxic zones; or 4) reduce demand for oxygen by reducing activity. However, these are all short-term strategies and will not enable the animal to survive long hypoxic periods. Adaptations are well developed in animals such as intertidal and burrowing animals that commonly experience hypoxia but poorly developed in animals that inhabit well-oxygenated environments such as the upper water column. If oxygen deficiency persists, death will ensue. Sublethal effects also occur. For example, reduced motor activity from mild hypoxia may make the animal more vulnerable to predators or decrease its growth or reproduction. Changes in the survival and reproduction of benthic and pelagic organisms can result in a cascade of effects including loss of habitat and biological diversity and altered food webs (EST, MAR, WARM, COLD, COMM, SPWN, MIGR), development of foul odors and taste (REC1), and degraded aesthetics (REC2; NRC 2000). Sutula (2011) provides a complete review of effects of DO on invertebrate and fish species of California estuaries.

Assessment of DO as a line of evidence of eutrophication was conducted using two types of datasets: 1) continuous DO, monitored at five stations intermittently over a period of 8 years and 2) discrete water quality measurements, measured at five stations consistently in the early morning over a period of 15 years (Table 4, Figure 3).

**Table 4. List of stations and deployment dates for continuous DO data.**

| Station | Longitude | Latitude | Dates of Deployment |
|---|---|---|---|
| Nature Center | -117.273 | 33.01166 | Dec 2008 - Nov 2010; June 2012 - Current |
| Dike | -117.26 | 33.00932 | Jan 2014 - Current |
| I-5 | -117.265 | 33.00986 | August 2015 - March 2016 |
| Rios | -117.269 | 33.00511 | July 2015- Current |

In assessing the status and trends of DO in the Lagoon, two sets of benchmarks were utilized: 1) existing San Diego Water Board Badin Plan DO water quality objectives (WQO) of 5 mg/L, assessed as the 10$^{th}$ percentile of 7-day average DO minima and 2) an assessment framework, adapted from the EU WFD approach (Best et al. 2007), which utilizes a suite of benchmarks representative of acute and chronic DO criteria derived for non-salmonid fish and invertebrates found in California bar-built estuaries (Sutula et al. 2013; Table 5). This second set of benchmarks were utilized to explore the duration of suboptimal DO events within the Lagoon, classifying events on timescales from hourly, and monthly events.

**Table 5. Assessment framework of ecological condition based on DO in California bar-built estuaries that are host to non-salmonid fish. Adapted from Best et al. (2007) and Sutula et al. (2013).**

| Ecological Condition Category | Representative DO Range | Rational |
|---|---|---|
| Very High | ≥ 5.8 mg $L^{-1}$ | High quality waters, supports all life stages of non-salmonid fish and invertebrates |
| High | 5.0 - 5.8 mg $L^{-1}$ | Supports all life stages of non-salmonid fish and invertebrates |
| Moderate | 4.0 - 5.0 mg $L^{-1}$ | Supports presence of non-salmonid fish and invertebrates, moderate larval recruitment of fish and invertebrates, depending on duration |
| Low | 2.8 - 4 mg $L^{-1}$ | Supports presence, but poor larval recruitment of fish and invertebrates |
| Very low | < 2.8 mg $L^{-1}$ | Marginal survival of resident species at short-term durations (timescales of hours) |

## 2.3 Assessment of BMI Community Data

BMI play a critical role in the biotic and abiotic functioning of the estuary; thus, a diverse, fully functional macrobenthic community is an essential part of maintaining ecosystem services and related estuarine beneficial uses. The State of California has designated six “Estuarine Beneficial Uses” upon which to evaluate the estuarine natural resources (structure) and ecosystem services (function). These beneficial uses broadly address biodiversity and threatened/endangered species (rare [RARE], spawning [SPWN], and migratory [MIGR] uses), commercially valuable resources (commercial [COMM], shellfish [SHELL], and aquaculture [AQUA] uses), and the inherent value estuarine habitat for aquatic life (estuarine [EST] and wildlife [WILD] uses). The structure and function of the BMI community encompasses: 1) their contribution to estuarine and marine biodiversity; 2) direct recreational and fisheries harvest; 3) a food resource for a variety of estuarine aquatic life forms, including fish, birds, and marine mammals; 4) a critical role in the maintenance of water column and sediment biogeochemical cycling; and 5) the consumption of a variety of organic matter sources and subsequent regeneration of nutrients to the water column. From the estuarine beneficial use perspective, macrobenthos are part of diversity of aquatic life and as such a direct measure of EST beneficial uses. The State of California has recognized the intrinsic value of BMI and as such, has develop estuarine sediment quality objectives and stream biointegrity policies that includes BMI as a primary indicator of aquatic life.

Eutrophication primarily affects BMI via indirect paths of water column hypoxia/anoxia or the accumulation of toxic reduced sulfides and ammonia in the sediment. Even in natural, non-eutrophic conditions, these processes occur in both muddy and sandy sediment environments and the fauna that live there are adapted to deal with low-oxygen, reducing environments. However, as the amounts of organic matter produced and accumulated in the system increases, low oxygen and reduced conditions begin to expand and either smother or poison the benthic fauna. These processes lead to progressive changes in the abundance, biomass, and composition of the macrobenthic community (Figure 5) and eventually lead to azoic conditions (devoid of life).

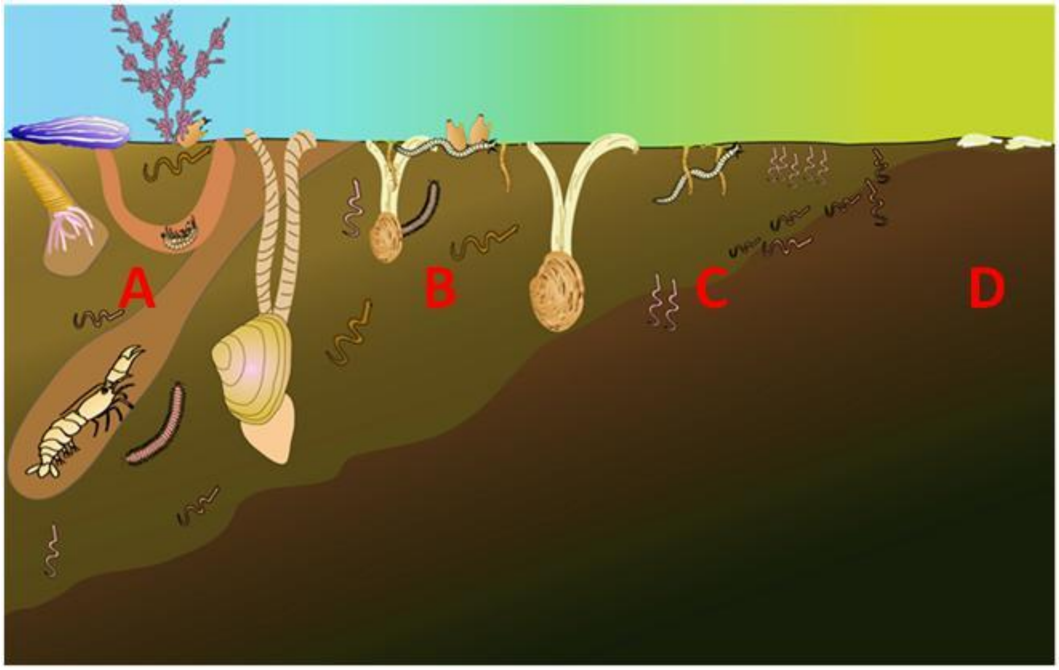



**Figure 5. An illustration of the Pearson-Rosenberg (1978) conceptual model depicting changes in macrobenthic community structure with increasing eutrophication and organic matter accumulation in the sediment. For discussion purposes, the model has been subdivided to highlight four primary condition categories associated with such increases: A – Non-eutrophic, B – Intermediate Eutrophication; C – Severe Eutrophication; and D - Anoxic bottom water and azoic sediments.**

Analyses of existing Southern California Bight Regional surveys and MS4 permit monitoring programs were conducted to determine whether eutrophication appears to be impacting the BMI community composition in the Lagoon. Data from 21 sites collected from 2003-2013 were used to conduct two types of analyses: 1) calculation of benthic habitat quality scores, using the California Sediment Quality Objectives (SQO) Benthic Line of Evidence (BLOE) assessment framework (Ranasinghe et al. 2009; Bay et al. 2012) and 2) analyses of benthic community composition data for information on possible stressors, such as eutrophication (low DO, organic matter accumulation) versus other stressors that might depress benthic habitat quality scores but are unrelated to eutrophication-related stress.

# III. Results and Discussion

## 3.1 Macroalgal Biomass and Cover

While macroalgae are important and natural component of an estuary (Kwak and Zedler 1997, McGlathery 2001), their excessive abundance can reduce the habitat quality of a system. An overabundance can lead to depletion of DO from the water column, causing hypoxia (low DO) or anoxia (no DO) (Diaz 2001, Diaz and Rosenberg 1995; macroalgae can also shade out or smother other primary producers and reduce benthic habitat quality through the stimulation of sulfide and ammonium production (Diaz 2001).

During the two years in which data are available, macroalgal biomass and cover peaked in the 2008, with intermediate levels of biomass and high percent cover at both Segment 1 and 2, causing them to score in the “moderate” category (Table 6). During the subsequent year in Segment 2, biomass and cover was roughly half that of the previous year, causing the segment to score in the “high” ecological condition category. No data were available from Segment 2 in 2009. During both years, biomass was just below, but within standard error, of the numeric target of 57 g dw $m^{-2}$ proposed for Santa Margarita River Estuary.

**Table 6. Summary of Growing Season Macroalgal Biomass and Percent Cover Data For San Elijo Lagoon During 2008- 2009.**

| Study | Time Period | Dry Weight Biomass (Mean ± SD) g $m^{-2}$ | % Cover (Mean ± SD) |
|---|---|---|---|
| **Segment 1** | | | |
| TMDL Monitoring Order | 2008-July | 50.2±27.3 | 67±15 |
| | 2008-September | 12.2±5.0 | 9±1 |
| Bight 08 Study | 2008-November | 17.0±8.9 | 37.8±20.3 |
| | 2009-May | 15.5±14.2 | 20.6±3.7 |
| | 2009-July | 14.0±1.1 | 41.7±7.0 |
| | 2009-October | 17.0±11.4 | 25.8±28.8 |
| **Segment 2** | | | |
| TMDL Monitoring Order | 2008-April | 3.4±2.5 | 73.6±13.2 |
| | 2008-July | 39.8±11.6 | 73.3±8.1 |
| | 2008-September | 8.1±2.8 | 85.6±7.0 |

### 3.2 DO

DO is necessary to sustain the life of all aquatic organisms that depend on aerobic respiration. Eutrophication produces excess organic matter that fuels the development of low surface water DO concentrations (hypoxia) as that organic matter is respired (Diaz 2001). When the supply of oxygen from the surface waters is reduced or the consumption of oxygen exceeds the resupply (via decomposition of excessive amounts of organic matter), oxygen concentrations can decline below the limit for survival and reproduction of benthic (bottom-dwelling) or pelagic (water column dwelling) organisms (Stanley and Nixon 1992, Borsuk et al. 2001, Diaz 2001). Hypoxia has a number of adverse effects on aquatic organisms, including: lowered growth rates, altered behavior, reduced reproductive success, and diminished survival (Diaz and Rosenberg 1995; Breitburg et al. 1997, 2009; Vaquer-Sunyer and Duarte 2008). Changes in the survival and reproduction of benthic and pelagic organisms can result in habitat and biological diversity losses and altered food webs.

The Lagoon consistently does not meet San Diego Water Board Basin Plan DO WQOs, based on continuous DO monitoring data from all stations and across all years (Table 7). Annually, the percentile of data in which the 7-day mean of DO minima > 5 mg/L ranged from 0 to 78 across sites and years. Summer was clearly the critical period, with most sites and years recorded using continuous monitoring never or nearly never meeting the WQO during this season (Table 7).

**Table 7. Assessment of San Elijo continuous DO monitoring sites over various years, utilizing Water Board Basin plan WQO (based on 7-day average of DO minima). See Figure 3 for site designations and locations. DO data were assessed on a hydrological year (November 1- October 30), with winter = November 1- March 31 and summer = April 1- October 31st.**

| Site | Year | 10th Percentile | | | Percentile of data in which 7-day mean of DO minima > 5 mg/L | | |
|---|---|---|---|---|---|---|---|
| | | Annual | Winter | Summer | Annual | Winter | Summer |
| OI | 2007-08 | 1.0 | 4.8 | 0.9 | 27.3 | 85.4 | 0.5 |
| DIKE | 2013-14 | 0.5 | 7.2 | 0.4 | 28.8 | 100.0 | 13.9 |
| | 2014-15 | 1.3 | 2.2 | 0.9 | 21.2 | 51.0 | 1.0 |
| | 2015-16 | 4.3 | 4.3 | n/a | 82.2 | 82.2 | n/a |
| NC-1 | 2008-09 | 1.2 | 5.1 | 1.0 | 30.4 | 92.8 | 0.0 |
| | 2009-10 | 1.0 | 3.3 | 0.9 | 24.3 | 58.8 | 0.5 |
| | 2011-12 | 1.2 | n/a | 1.2 | 1.7 | n/a | 1.7 |
| | 2012-13 | 0.7 | 4.5 | 0.5 | 31.2 | 77.2 | 0.0 |
| | 2013-14 | 0.6 | 1.0 | 0.4 | 4.1 | 9.5 | 0.0 |
| | 2014-15 | 1.2 | 0.9 | 1.2 | 3.1 | 9.5 | 0.0 |
| | 2015-16 | 3.5 | 3.5 | n/a | 76.0 | 76.0 | n/a |
| NC-2 | 2007-08 | 1.1 | 2.0 | 1.0 | 21.0 | 70.0 | 2.0 |
| RIOS | 2014-15 | 1.0 | n/a | 1.0 | 0.0 | n/a | 0.0 |
| | 2015-16 | 2.5 | 5.4 | 0.5 | 78.6 | 92.8 | 0.0 |
| I-5 | 2007-08 | 1.1 | 5.8 | 1.0 | 39.9 | 100.0 | 14.0 |

Binning continuous DO concentrations along a continuum of high quality (> 5.8 mg/L DO) to acceptable (> 5 mg/L) to low quality waters (< 2.8 mg/L) provides a better sense of overall distribution of the data (Table 8). Overall, during the winter period (November 1 – March 31), DO concentrations were of fairly high quality, with a median of 94% and range of 56-99% of the time spent above 5 mg/L across sites. During the summertime, however, DO was in suboptimal conditions typically at least half the time, with hypoxia occurring all sites from 15-76% of the time across all sites.

**Table 8. Percent of time that continuous DO at San Elijo monitoring sites was within benchmarked values from < 5.8 mg/L to < 2.8 mg/L during summertime (April 1- October 31) over various years. See Figure 3 for site designations and locations.**

| Sites | Year | April - October DO Distributions (% of Time) | | | | |
|---|---|---|---|---|---|---|
| | | > 5.8 mg/L | 5.0 - 5.8 mg/L | 4.0 - 5.0 mg/L | 2.8 - 4.0 mg/L | < 2.8 mg/L |
| OI | 2007-08 | 58 | 9 | 9 | 9 | 15 |
| DIKE | 2013-14 | 20 | 13 | 19 | 20 | 27 |
| | 2014-15 | 29 | 13 | 16 | 16 | 26 |
| NC-1 | 2008-09 | 52 | 9 | 10 | 11 | 19 |
| | 2009-10 | 42 | 9 | 11 | 13 | 26 |
| | 2011-12 | 47 | 9 | 11 | 12 | 21 |
| | 2012-13 | 33 | 9 | 11 | 16 | 30 |
| | 2013-14 | 38 | 10 | 12 | 13 | 27 |
| | 2014-15 | 43 | 12 | 13 | 16 | 16 |
| NC-2 | 2007-08 | 48 | 8 | 10 | 13 | 21 |
| RIOS | 2014-15 | 33 | 9 | 12 | 19 | 27 |
| | 2015-16 | 1 | 4 | 8 | 10 | 76 |
| I-5 | 2007-08 | 37 | 9 | 13 | 16 | 25 |
| | 2014-15 | 16 | 13 | 18 | 22 | 31 |

During the summer, most of the low DO events were high frequency, short duration events on time scales of 2-12 hours within the range of 2.8- 5.0 mg/L (Figure 6). Hypoxic events (< 2.8 mg/L) of moderate duration (>12 hours) were equally frequent as short duration events (< 2 hours) and often enough to be of significant concern for the potential impact on biological resources. These patterns are consistent with estuaries with high sediment organic matter content and resulting sediment oxygen demand, resulting in strong diurnal variability (McLaughlin et al. 2013).

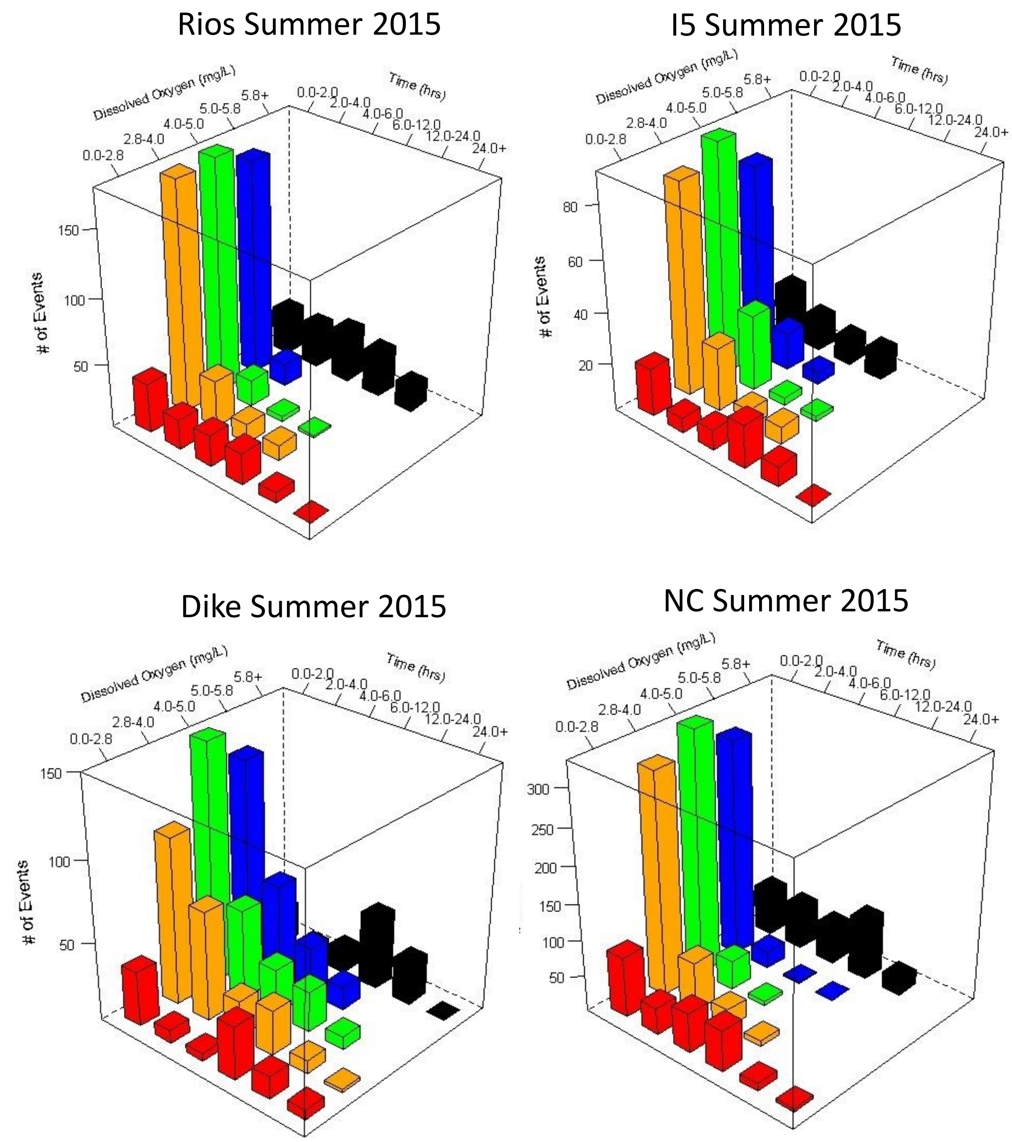



**Figure 6. Plots of the frequency and duration of DO events, from high oxygen concentration (> 5.8 mg/L) to hypoxia (< 2.8 mg/L) during summertime periods in the four main Lagoon sites during the summer 2015: Rios, Dike, NC and I-5. Height of the bar is the number of DO events binned by benchmarks of concern (mg/L) and by time (hours).**

This strong diurnal variability is visible in contour plots of DO concentration as a function of hour of the day versus time (Figure 7), occurring consistent from ~ midnight through noon. At sites such as the Nature Center with more tidal circulation, a strong spring-neap tidal signature at a bi-weekly frequency is visible in the data. This spring-neap variability is largely absent at the Dike site. At this site, the lack of tidal exchange results in DO concentrations that are largely hypoxic at night, particular during late summer. High temperatures are likely the major driver for late summer chronic hypoxia; water temperature was significantly correlated with seasonal cycles in daily DO minima (Figure 8); temperature is a well-documented driver of increased sediment oxygen demand, hypoxia and eutrophication symptoms (Paerl 2006). Given regional increases in temperature predicted to occur with climate change, it is likely that Southern California estuaries such as San Elijo Lagoon will be experiencing increases in eutrophication symptoms in the future, particularly those that are plagued with high sediment organic matter accumulation.

Finally, the discrete water quality monitoring data set provided a consistent means to evaluate spatial trends in DO over time. Understandably, DO is typically the highest near the mouth proximal to ocean sources of well-oxygenated water, and trends downward upstream.

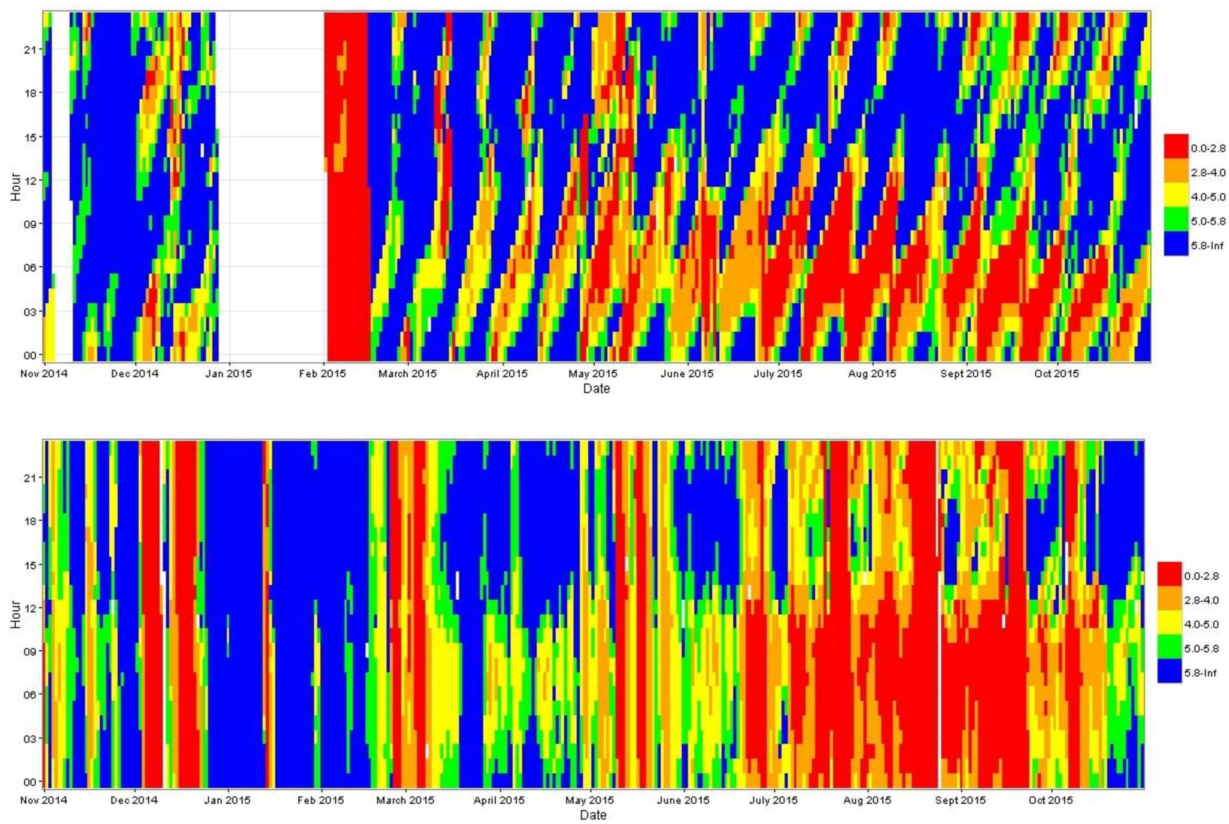



**Figure 7. Contour plots of DO concentrations as a function of time of day versus spring-fall date, binned to represent benchmarks of physiological effects, from no effects/high quality (blue) to acute, lethal effects/poor quality hypoxic waters (red). Panels represent the Nature Center (top panel) and Dike (bottom panel) sites during 2014-2015 hydrological year.**

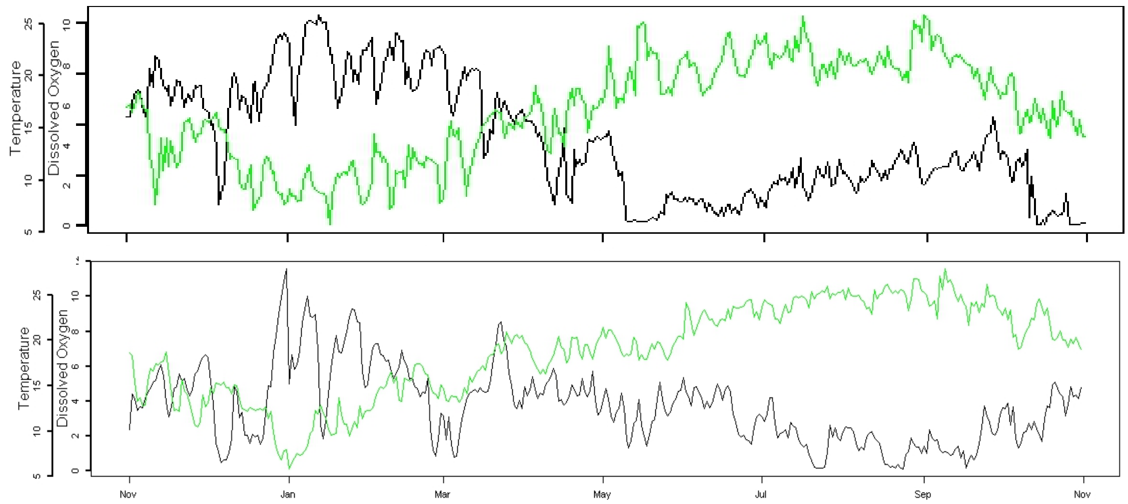



**Figure 8. Time series data showing continuous temperature (green) and daily DO minima (black) for the Nature Center (top panel) and Dike stations (bottom) during the period of November 1, 2014-October 31, 2015.**

### 3.3 BMI

BMI are one of the primary tools used to assess the ecological condition of estuaries and coastal nearshore habitat because 1) they live in bottom sediments, where many stressors accumulate; 2) most macrobenthos are sedentary and therefore, reflect the quality of their immediate environment (Pearson and Rosenberg 1978, Dauer 1993, Weisberg et al. 1997); 3) most communities are comprised of a diverse array of species with a variety of tolerances to stress, so the presence or absence of different taxa can provide information about the types of stressors present (Christman and Dauer 2003; Lenihan et al. 2003); and 4) they serve as food sources for many ecologically and economically important estuarine fish and birds (Virnstein 1979, Pihl et al. 1995, Gillett 2010). Macrobenthic community-based assessment tools such as the sediment quality benthic line of evidence (BLOE, Ranasinghe et al. 2009; Bay et al. 2012) have traditionally been designed to assess overall habitat quality; integrating a variety of anthropogenic stressors (e.g., contaminants, eutrophication, or physical disturbance) while accounting for gradients in natural stressors/environmental conditions (e.g., salinity, sediment type, or depth). Interpretation of BMI community composition data can be translated through the lens of the CA SQO BLOE index. In this assessment framework, categories of reference and low to high impact refer to levels of benthic ecological condition, from excellent (reference) to poor ecological condition (high impact).

Analyses of BLOE scores from 21 sites in the Lagoon indicate benthic habitat at nearly all of the sites are in the highly disturbed condition category throughout the period of 2003-2013 (Table 9). The few samples that were in moderate to low disturbance condition were all located relatively close to the mouth of the lagoon. It should be noted, that macrobenthic samples from the middle and upper parts of the lagoon had salinities lower than 27 psu. Consequently, they were outside of the condition for which the index was calibrated (Bay et al. 2012) but the scores could still be used in a comparative framework among other low salinity samples. Despite the low SQO BLOE scores, the absence of significantly high levels of contaminants in the sediment and relatively little observed toxicity would suggest that toxic chemicals are not the root cause of the altered benthic community structure the BLOE would indicate. Unfortunately, with the exception of 2008, there was not a consistent spatial allocation of the macrofaunal samples across the length of the estuary, limiting us our ability to make additional inferences with respect to spatial and temporal trends.

Beyond the three measures of the SQO framework, there are alternative approaches to understanding the altered nature of the benthic assemblages of San Elijo Lagoon. A look at the significant changes in benthic community composition from sample to sample and year to year indicates that there were likely multiple, co-occurring stressors affecting the biota of the lagoon. This notion is further supported by the patterns in salinity and DO data from the lagoon.

There appears to be abundant nutrients and primary production in the system given the dominance of snails (grazers of macroalgae and benthic microalgae), interface feeding spionid polychaetes in 2003-2004, and the very high abundances of deposit feeding amphipods in 2008-2013 samples. Most of these taxa are quite normal to have in mesohaline environment, but their high abundance and dominance – paired with relatively high abundances of capitellid polychaetes suggests an accumulation of organic matter in the sediments. Thus sediment organic matter accumulation is one likely reason for depressed SQO BLOE scores. Given the high abundance and diversity of crustaceans, it is unlikely that low DO alone is impacting the benthic communities and possibly reflects that much of the Lagoon is dominated by intertidal sediments. The exception to this pattern of minimal low DO impacts is upstream station B08-6242 (collected in 2008), proximal to the Dike DO station. Unlike the other stations from 2008, that station had very low abundance, taxa richness (i.e., contained only 4 taxa), and was not dominated by crustaceans, all of which suggests the station was likely defaunated by persistent low DO.

Though the organic matter accumulation and low or fluctuating DO likely set a baseline community (i.e., lots of deposit feeders and grazers), salinity fluctuations appear to be just as important; especially in the year-to-year and upstream/downstream differences among benthic samples. Salinity fluctuations on the tidal cycle are normal for estuarine systems and create niche space for "normal" estuarine endemic taxa that can tolerate the salinity fluctuations (e.g., spionid, capitellid, and hesionid polychaetes, corophriid amphipods, etc.; e.g., Boesch 1976; Gillett and Schaffner 2009). These types of samples were most evident in the upper 2/3rds of the estuary (i.e., above station SEL-11). The samples from the lower portions of the estuary were more similar to those from stable, higher salinity embayments in Southern California. The 2005 samples were an anomaly, as some were nearly devoid of any fauna and the animals that were present were primarily low salinity fauna (insect larvae and low salinity amphipods). This anomalous shift to oligohaline-type taxa suggests very low salinity across the estuary in 2005, possibly precipitated by a closure of the estuary's mouth. In normal years however, it appears salinity fluctuation is most important to the benthic infauna in the mid- to upper portions of the estuary.

**Table 9. Summary of SQO BLOE scores for San Elijo Lagoon over the period of 2003-2013.**

| Year | Station ID | SQO BLOE Score | SQO BLOE Condition Category |
|---|---|---|---|
| 2003 | SEL-2M1 | 4 | High Disturbance |
| 2003 | SEL-3L4 | 4 | High Disturbance |
| 2004 | SEL-2L1 | 4 | High Disturbance |
| 2004 | SEL-3L2 | 4 | High Disturbance |
| 2004 | SEL-3R1 | 4 | High Disturbance |
| 2005 | SEL-2L2 | 4 | High Disturbance |
| 2005 | SEL-3L3 | 4 | High Disturbance |
| 2005 | SEL-3R1 | 4 | High Disturbance |
| 2008 | B08-6239 | 4 | High Disturbance |
| 2008 | B08-6242 | 4 | High Disturbance |
| 2008 | B08-6243 | 3 | Moderate Disturbance |
| 2008 | B08-6244 | 4 | High Disturbance |
| 2008 | B08-6245 | 4 | High Disturbance |
| 2011 | SE11-1A | 3 | Moderate Disturbance |
| 2011 | SE11-1B | 2 | Low Disturbance |
| 2011 | SE11-1C | 4 | High Disturbance |
| 2011 | SE11-2A | 4 | High Disturbance |
| 2011 | SE11-2B | 4 | High Disturbance |
| 2011 | SE11-2C | 4 | High Disturbance |
| 2013 | B13-8188 | 4 | High Disturbance |
| 2013 | B13-8189 | 3 | Moderate Disturbance |

Multiple stressors can act in concert to depress benthic invertebrate scores. There is no evidence for toxic contaminants driving condition. Additionally, there was little evidence for physical disturbance within the lagoon aside from sample B13-8188 (collected in 2013). This one sample had very low abundance and taxa richness. However, the fact that the taxa that were present were higher salinity taxa, and that the sample was located right in the mouth of the lagoon, suggests that physical disturbance of the sediment surface by wave action led to the depauperate community.

Overall, the macrobenthic community data would suggest that excess organic matter accumulation, salinity, and DO were the primary structuring factors of community composition across the estuary. However, the pattern is spatially complicated, with salinity fluctuation (and possibly low DO) likely being more important in the upper portions of the estuary, with sediment organic matter having an important influence throughout. Furthermore, when the mouth of the estuary closes, there may be dramatic state changes in the lagoon where the macrobenthic community looks more like an oligohaline estuary than the normal polyhaline/mesohaline nature of San Elijo Lagoon. The low SQO BLOE scores were likely a function of both of these stressors, as the taxa that dominate in lower salinities and flourish in habitats where organic matter accumulates tend to be penalized by the SQO BLOE assessment framework in spite of little evidence for toxic chemicals in the system.

# IV. SUMMARY AND RELEVANCE FOR RESTORATION

## 4.1 Major Findings

Three lines of evidence were used to assess eutrophication status of San Elijo Lagoon: 1) macroalgal biomass and percent cover, 2) DO and 3) BMI community composition. Existing data from the period to 2003-2016 were interpreted through San Diego Basin plan WQOs, draft macroalgae and adopted BMI assessment frameworks.

We found that the Lagoon is failing to meet water and sediment quality objectives for two of the three lines of evidence (DO and BMI) and is meeting, but only nearly so, a proposed numeric target for macroalgae.

Macroalgal biomass and cover assessed over a 2-year period were in the moderate to high ecological condition category, with biomass (40-50 g dw $m^{-2}$) within measurement error of the proposed numeric target for Santa Margarita River estuary (57 g dw $m^{-2}$).

The DO dataset was the most extensive, monitored continuously at five sites and spanning from 2003-2016. These data indicate that during the spring-fall, DO in the Lagoon was in suboptimal DO conditions typically at least half the time (DO conditions that can affect fish reproduction, larval recruitment, and juvenile survival). Hypoxia, conditions that can cause acute mortality of fish and some invertebrate species, occurred at all sites from 15-76% of the time across all sites. Across sites, the Rios, I-5 Bridge and Dike locations were consistently worse than the Nature Center and (when measured) the Ocean inlet. During the summer, most of the low DO events were high frequency, short duration events on time scales of 2-12 hours within the range of 2.8-5.0 mg/L. The duration of these hypoxic events were at a frequency to be of significant concern for the potential impact on biological resources. Low DO was significantly correlated to temperature, a driver that is likely to increase with climate change.

The BMI data, spanning the same time period as DO, provide supporting evidence that eutrophication is having a biological impact, as nearly all of the sites are in a highly disturbed condition throughout the period 2003-2013. On the whole, the BMI community data suggest that excess organic matter accumulation, salinity, and DO were the primary structuring factors of community composition, with salinity fluctuation (and possibly low DO) likely being more important in the upper portions of the estuary, while sediment organic matter was an important influence throughout.

## 4.2 Relevance and Recommendations for Restoration of San Elijo

Lagoon restoration is an appropriate management action to consider improving the documented sediment and water quality problems, as these conditions appear to be significantly impacting DO, an essential element of good quality fish habitat, and benthic macroinvertebartes, the foundation for estuarine fish and (migratory) bird food webs. McLaughlin et al. (2010) noted that the efflux of nutrients associated with Lagoon sediment organic matter represents > 70% of total dry weather nutrient inputs to the Lagoon. This mechanism assures that eutrophication symptoms will continue, even if watershed nutrient loads are dramatically reduced, unless restoration is undertaken to alleviate the drivers of these symptoms.

Three types of restoration actions could improve eutrophication symptoms: 1) improved tidal exchange, reducing hydraulic retention times, 2) improving Lagoon circulation to flush out fine grained sediments and opportunities to allow water to stagnate, and 3) removal of sediments high in organic matter and nutrient content, particularly those associated with legacy sewage disposal. A combination of these actions are anticipated to be the most effective approach to address eutrophication in the system, as it would reduce *in situ* accumulated sediment organic matter within the Lagoon and minimize the accumulation of new sources of organic matter, thereby reducing eutrophication symptoms. These three actions are consistent with the preferred restoration alternative.

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